EIC Detector R&D Progress Report

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Abstract

Excellent particle identification (PID) is an essential requirement for a future Electron-Ion Collider (EIC) detector. Identification of hadrons in the final state is critical to study how different quark flavors contribute to nucleon properties. Reliable identification of the scattered electron is important for covering kinematics where pion backgrounds are large. The EIC PID consortium (eRD14) was formed to develop an integrated PID program using a suite of complementary technologies covering different ranges in rapidity and momentum, as required by the asymmetric nature of the collisions at the EIC. The PID consortium has also worked closely with BNL and JLab to ensure that the specific R&D projects are compatible with the detector concepts that are being pursued there.

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1. Introduction

Identification of hadrons in the final state is essential for key EIC measurements formulated in the EIC White Paper and referenced in the NSAC Long Range Plan. These include 3D imaging of the nucleon in momentum space through semi-inclusive DIS (where flavor tagging can tell us about the transverse momentum distributions and, potentially, the orbital angular momentum of the strange sea), and open charm (with decays of D-mesons into kaons), which is important for probing the distribution of gluons in protons and nuclei.

Satisfying the PID requirements within the very asymmetric kinematics of the EIC (discussed in detail in the eRD14 proposal for FY20) requires a suite of detector technologies that can address the specific challenges (in terms of momentum coverage, available space, *etc.*) encountered in various ranges of rapidity. Thus, the integrated PID program pursued by the eRD14 Consortium includes different detector systems for each endcap and the central barrel, as well as corresponding sensor and readout solutions. While we ensure compatibility with the detector concepts developed at BNL and JLab. All the funded R&D being pursued by the consortium is conceptually novel. The dual-radiator RICH (dRICH) for the hadron endcap is the first such design for a solenoid-based collider detector. The modular aerogel RICH (mRICH), primarily intended for the electron endcap, introduces lens-based focusing, which improves momentum coverage and reduces the required sensor area. The compact, high-performance DIRC for the solenoid barrel combines new optics for spatial imaging with good timing (<100 ps rms) to allow a significant improvement in momentum coverage compared with the state-of-the-art. The funded work on photosensors in high magnetic fields and on adaptation of LAPPDs to EIC requirements is also aimed at developing a new generation of devices. Starting in FY18, the sensor effort has been extended to include corresponding readout electronics.

At the end of FY19 the consortium was asked to develop a four-year plan to reach readiness to write a technical design report (TDR). The plan was presented during the in-depth review of the eRD14 collaboration, on September 19, 2019. https://indico.bnl.gov/event/6819/

The first year of the plan coincided with the FY20 proposal, presented to the committee in July, but envisioned an increase in funding for FY21-23 as the consortium would transition from generic to targeted R&D. For FY20, the top priorities were to transfer the PANDA DIRC prototype to the US, start building the dRICH prototype, and to investigate whether LAPPDs could become a viable photosensor solution for the EIC. We are grateful for the positive and constructive feedback from the committee.

The consortium has also been closely following the spending of the approved funds. Since funds do not become available at the beginning of the year, and the handling of invoices can be slow at some institutions, there could be an appearance of unspent funds during a year, but eRD14 does not have a significant actual carryover in FY19, nor is one expected in FY20.

2. Hadron Identification Detectors

2.1 Summary

The funded R&D on the three Cherenkov systems has been proceeding very well, and they all promise significant advances over the fallback options (single-radiator gas RICH for the dRICH, proximity-focusing aerogel RICH for the mRICH, or a DIRC geared only towards spatial imaging or timing).

2.2 Dual-Radiator RICH (dRICH)

The dual Ring Imaging Cherenkov (dRICH) detector is intended to provide full hadron identification (π/K/p separation of better than 3 sigma) from ~3 GeV/*c* to ~50 GeV/*c* and electron identification (e/π separation) up to about 15 GeV/*c*, in the ion-side end cap of the EIC detector. The simulated geometry covers angles up to 25°.

2.2.1 Past

2.2.1.1 What was planned for this period?

The main technical goals for 2019 were: consolidation of the prototype design (to begin component procurement), finalization of a novel approach for the optimization of the detector design driven by Artificial Intelligence (AI) methods, and publication of the event-based reconstruction algorithm. Moreover, a new co-funding request for prototyping (both dRICH and mRICH) was expected to be submitted to the Italian National Institute of Nuclear Physics (INFN).

2.2.1.2 What was achieved?

The design of the dRICH prototype elements has been detailed in preparation for the procurement phase. The vessel dimensions and the flange layout have been fixed and a mirror support and alignment system has been elaborated. The latter uses 3 z-axis vacuum manipulators with spherical joints to translate and rotate the mirror support, while the mirror weight load is sustained by a carriage free to run along a z-axis rail as shown in Fig. 2.2.1. As one of the manipulators is connected to the carriage, the system allows to translate the mirror to adjust the focal length, and to align it during working conditions when the vessel is pressurized. This opens the possibility to use a mirror with a central hole for the aerogel. Depending on the longitudinal position of the mirror, one can image the Cherenkov cone generated by only the aerogel, only the gas, or both radiators. All the access points are concentrated onto the vacuum flanges.

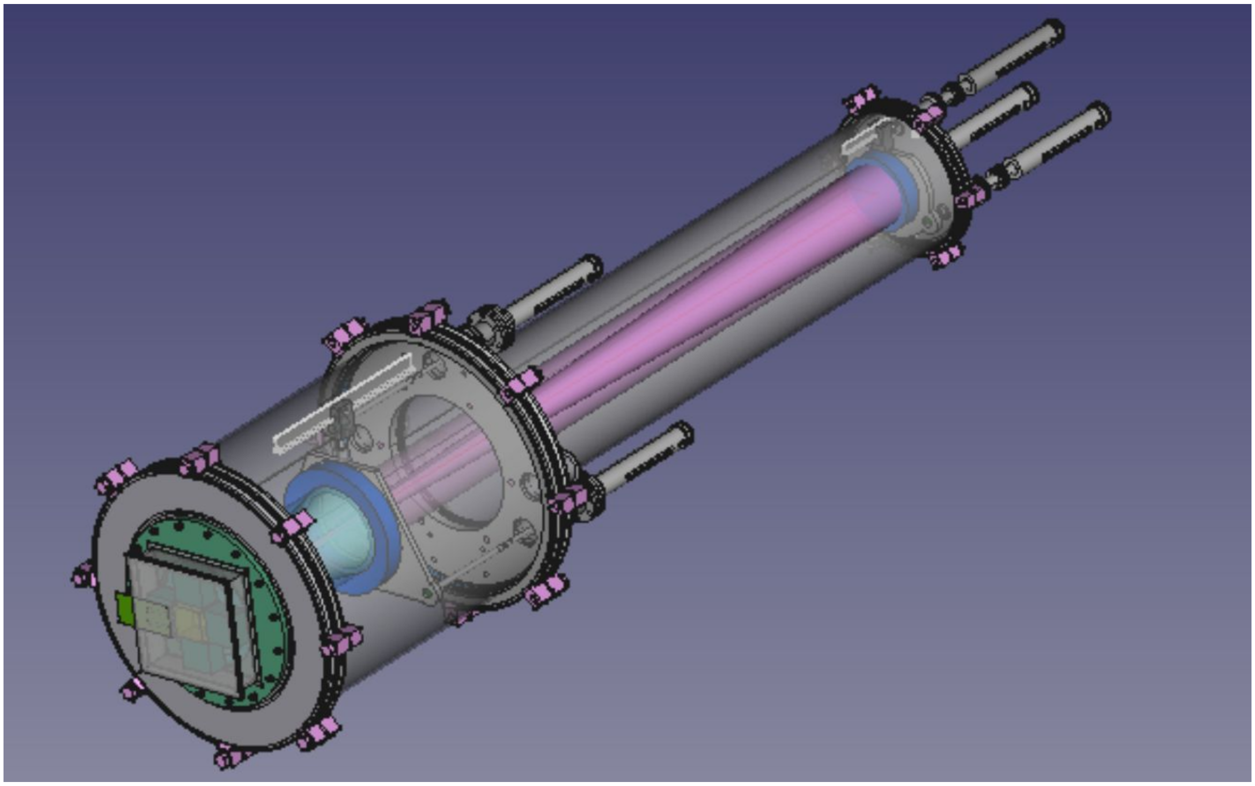


Figure 2.2.1: Layout of the mirror support and alignment system, based on 3 z-axis manipulators connected through spherical joints to the mirror support.

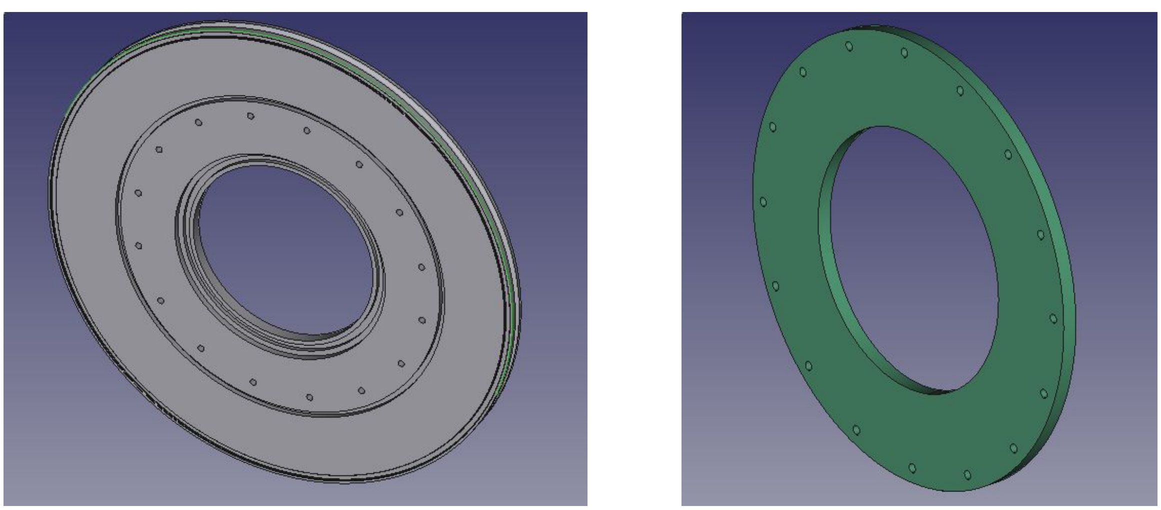


Figure 2.2.2: Design of the entrance flange (on the left) with its counter-flange (on the right) for fixing the optical window.

Having defined the mirror system, the vessel and flange design were completed. The procurement of the mechanics has been initiated.

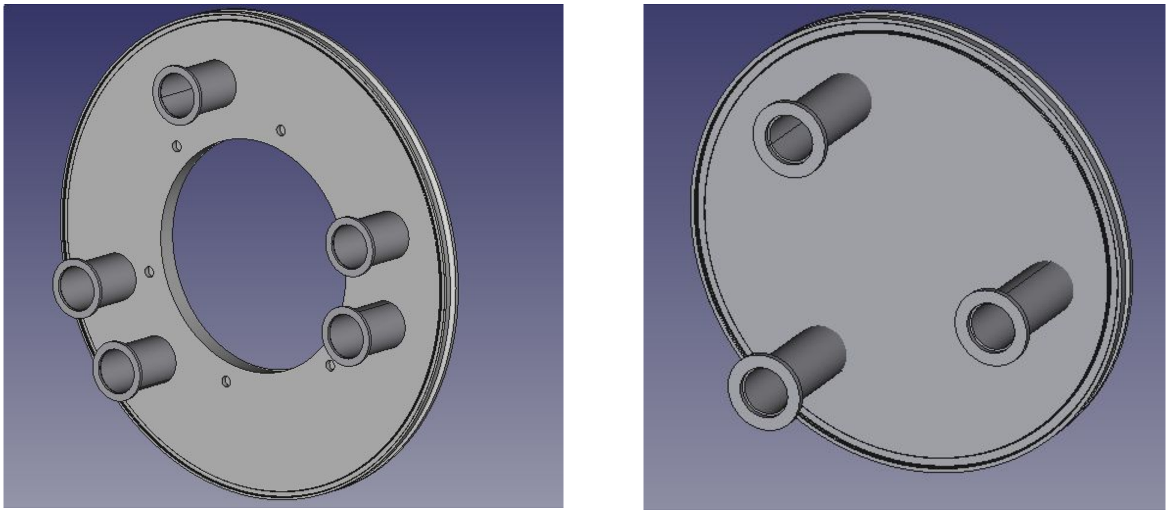


Figure 2.2.3: Design of the connecting (on the left) and exit (on the right) flange with their access points.

Using INFN funds, a contract has been awarded for the standard vacuum parts, and another contract is in preparation for the custom realization (flanges). Quotations have been collected for the freon gas. Also, several samples of aerogel have been ordered from the Russian producer, with refractive indices between 1.02 and 1.03 and dimensions suitable to serve both the dRICH and mRICH prototype-test campaigns. In parallel, the R&D work on optical aerogel at Aspen (USA) is being monitored. INFN funds have been granted for 2020. These funds will be instrumental for the mirror-system realization.

Within INFN, promising contacts have been pursued with new groups interested in the SiPM application for Cherenkov imaging. The collaboration with these groups may open the possibility to perform preliminary beam tests at the PS facility at CERN. Also, the INFN group is collaborating with JLab to use the pair spectrometer in Hall D, complemented by a tracking system, as a facility for detector tests. These facilities would facilitate the development and optimization of the Cherenkov prototype optics and readout.

An original approach based on Bayesian optimization [Sno12] and machine learning was finalized, implemented, and applied to the dRICH design. The implemented method [Cis19] essentially encodes the detector requirements and then searches for the global optimum of a proper figure of merit, keeping the number of iterations required to identify the optimal value relatively small. It is a general approach that can be extended and applied to other detectors and possibly to the entire experiment.

Using this approach, further improvement of the dRICH performance, compared to the consolidated baseline, has been obtained with a fine tuning of the following 8 configuration parameters, inspired by previous studies [Dot17]: the refractive index and thickness of the aerogel radiator; the focusing mirror radius, its longitudinal (which determines the effective thickness of the gas) and radial positions (corresponding to the axis going in the radial direction in each of the six mirror sectors; and the 3D shifts of the photon sensor tiles with respect to the mirror center on a spherical surface, which to some extent determines the sensor area and orientation relative to the mirror.

These parameters cover rather exhaustively the two major components of the dRICH: its radiators and optics. They have been chosen to improve the dRICH PID performance, under the constraint that it is possible to implement any values resulting from the optimization with (at worst) only minor hardware issues to solve. A minimum feasible tolerance on each spatial alignment parameter of 100 μm has been assumed, whereas for the aerogel, 1 mm on the thickness and 0.2% on the refractive index has been used. A relevant parameter was essentially neglected in the optimization: the gas refractive index. The tuning of this parameter would require either a pressurized detector or a gas mixture, making it a design leap. In this optimization, the magnetic field map of the JLab EIC spectrometer design at 2.5 T central field was used. In a more general approach, the B-field map could be part of the optimization.

The figure of merit takes into account the angular separation between pions and kaons in the aerogel-gas transition region (around 15 GeV/*c*) and at the highest achievable momentum (around 60 GeV/*c*). The optimization of the TOF-aerogel transition region (at low momenta) has not been considered, as earlier R&D carried out by the consortium suggests that it should be well within reach using state-of-the-art technologies for distances relevant to the dRICH. The parameter space can be extended once detailed results from prototyping and tests become available. Figure 2.2.4 reports the obtained improvement in the pion-kaon separation with respect to the original baseline: there is a better overlap in the transition region between aerogel and gas and extended highest momentum.

Results of this work have been presented at DIRC2019 and an article has been submitted for publication.

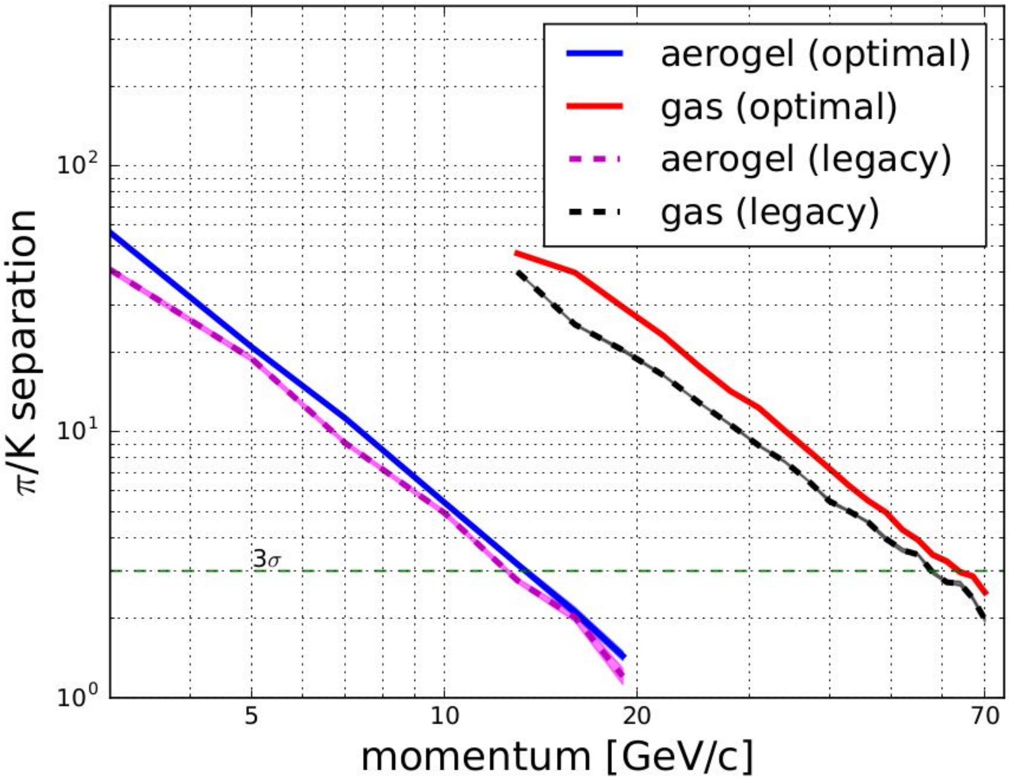


Figure 2.2.4: Improved pion-kaon separation as achieved by the Bayesian optimization approach, compared to the original baseline design [Dot17]. The curves are drawn with 68% C.L. bands.

The event-driven PID reconstruction method developed in 2018 was further investigated in order to better understand the identification mechanism and to improve its performance. The method uses the Inverse Raytracing (addressed in a previous report) to determine the emission angle corresponding to each photon hit, given a hypothesis about the particle type for each track in the event. The best hypothesis is the one that maximizes an associated likelihood. However, in order to reduce the computational effort (number of hypotheses), the method splits the reconstruction into two likelihoods that correspond to two main steps:

1) Sequential hit association to tracks/radiators using a first likelihood L1.
2) Once all hits are associated, one estimates a global likelihood (L2) for each track – particle combination. One then chooses the combination yielding the maximum L2.

The original L1 was the product of a Gaussian distribution, taking into account the degree of correlation of the reconstructed and expected angle, and a Poisson distribution providing the probability to assign a new photon to a track-radiator-particle hypothesis, by random choice. We carried out a detailed study of alternative choices of L1, which ended up with the conclusion that the L1 shall consist of only an ERF (Gaussian-Error) function of the reconstructed and expected Cherenkov angles (no Poisson distribution). The confusion matrices of the different L1 functions we considered are summarized in Fig. 2.2.5.

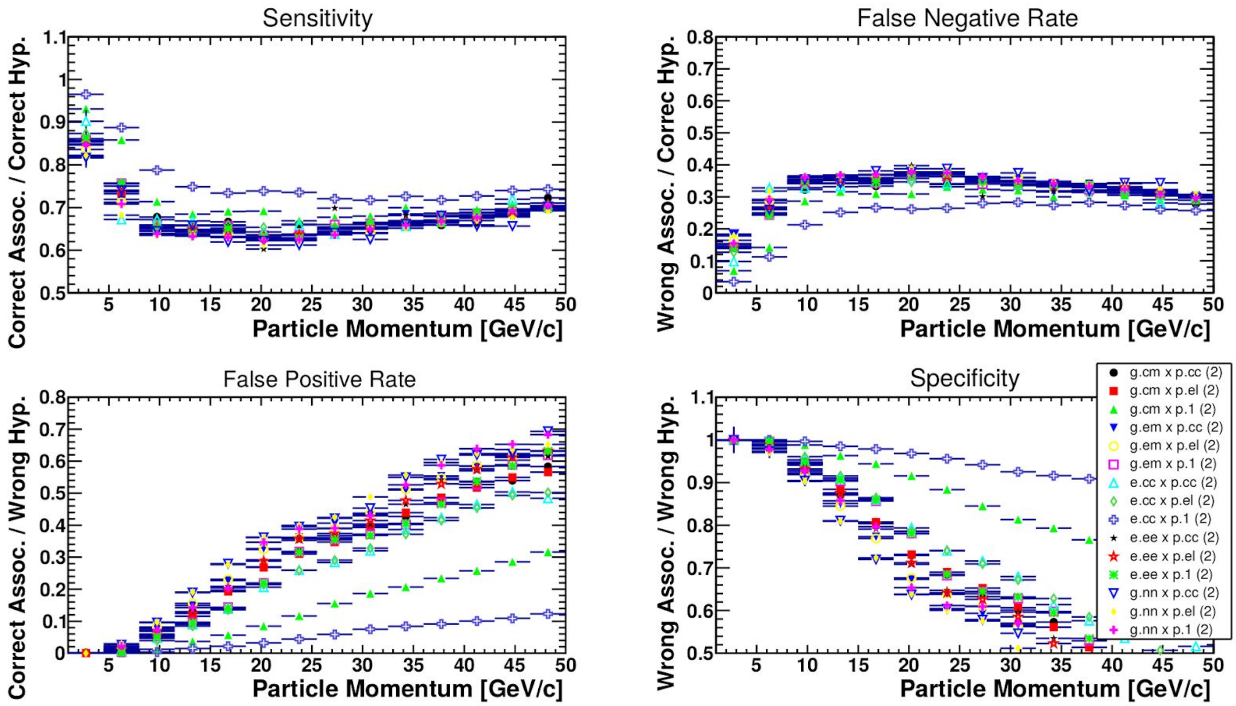


Figure 2.2.5: Confusion matrix of the different L1 alternatives (described in the list of the bottom-right legend): the best performance (largest sensitivity and specificity, smallest false negative and positive rates) is obtained with the use of the ERF function only (no Poisson distribution).

The originally planned circulation of the article reporting on the above reconstruction approach has been postponed due to the limited available resources diverted to the finalization of the optimization method and the preparation for the PID-EIC detailed review called by the R&D Committee in September 2019.

2.2.2 Future

2.2.2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The plan for 2020 is to start construction of the dRICH small-scale prototype. This activity will be carried out in strong synergy with the development of the readout electronics (*e.g.*, from Hawaii University) for the sensors for the mRICH prototype. In fact, all accomplishments for sensors and electronics for the mRICH prototype, apply directly to the dRICH prototype.

Specifically, our planned activities include:

1. Consolidated design finalization and implementation of a small-scale, flexible prototype that can host: aerogel, gas, mirror and either a matrix of SiPMs or other photon detectors (including GEM-based sensors, which are suitable for a gas-only RICH option).
2. Support of the development of a DAQ for the SiREAD chip. This will be done in synergy with the mRICH colleagues and in collaboration with JLab. Our responsibility is the integration and related tests of the back-end readout electronics.
3. Design finalization, construction, and tests of a SiPM matrix with proper cooling and thermal stability. Evaluation single-photon performance of existing SiPMs at the radiation levels expected at the EIC and study of mitigation solutions for SiPM, in particular regarding temperature control [Cal18] in conjunction with micro-cell geometry and fast-signal component pickup. Assessment of ongoing SiPM developments towards radiation-hard solutions.
4. Setup of a pulsed-laser test bench for characterization of optical sensors in conjunction with activity 2 above. A test bench will be useful for the evaluation and validation of readout electronics, for the definition of the best working parameters in preparation for beam tests, and for the evaluation of sensors radiation tolerance during future irradiation campaigns.

2.2.2.2 What are the critical issues?

Cost optimization by careful selection / customization / test of the major critical components, realistic validation of the Monte-Carlo predictions, and evaluation of technical details (that cannot be modeled by Monte Carlo methods) are very critical for the definition of a trustworthy TDR for the dRICH. A small-scale prototype is essential for this purpose and cannot be further delayed. The limited amount of funding is influencing its implementation. The limited funding obtained by INFN is being used to boost the prototype realization.

References:

[Sno12] J. Snoek, H. Larochelle, R.P. Adams, *Practical bayesian optimization of machine learning algorithms*, Adv. Neural Inf. Process. Syst., 2012, pp. 2951–2959. arXiv:1206.2944.

[Cis19] E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams *et al*., *AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case*, arXiv 1911.05797, 2019.

[Dot17] A. Del Dotto *et al*., *Design and R&D of RICH detectors for EIC experiments*, NIM A 876 (2017) 237–240.

[Cal18] M. Calvi *et al*., *Single photon detection with SiPMs irradiated up to 10^{14} cm^{-2} 1-MeV equivalent neutron fluence*, NIM A 922 (2019) 243.

2.3 Modular Aerogel RICH (mRICH)

This lens-based, compact, and modular Aerogel RICH detector provides hadron PID capability from 3 to 10 GeV/*c* (for π/K separation) and electron PID (for e/π separation) below 2 GeV/*c*. The details of this detector design can be found in the eRD14 FY19 proposal and in our mRICH publication [1]. In this report, we highlight progress made on the mRICH project since July of 2019 and describe further activities planned for FY20.

2.3.1 Past

2.3.1.1 What was planned for this period?

The planned major activities for this period included (1) data analysis of the second mRICH prototype beam test at Fermilab in Summer 2018; (2) implementation of an mRICH detector in the EIC Day-One-Detector based on sPHENIX; (3) preparation for the next mRICH beam test with tracking capabilities.

2.3.1.2 What was achieved?

The main achievements for the mRICH project during this report period are the following:

1) We focused on analyzing the mRICH test data for 120 GeV proton beam incident toward the central region of mRICH for assessing the mRICH performance. The preliminary results from this analysis are shown in Fig. 2.3.1. The corresponding results obtained from the mRICH GEANT4 simulation are shown in Fig. 2.3.2. There are noticeable differences in the results between the test data and the simulation. The contributing factors to these differences include mainly the lack of particle tracking in the beam test and precision optical alignment of mRICH components. In order to match with the test data in GEANT4 simulation, a significant effort was invested to improve the accuracy of the implementation of the detector components and the associated dimensions in the simulation. As an example, Fig. 2.3.3 shows the most up-to-date mRICH detector display and the sensor plane implementation in the GEANT4 simulation. Further study is currently ongoing.
2) We continued the effort of implementing an mRICH detector array in the EIC Day-One-Detector based on sPHENIX (see Fig. 2.3.4) using the Fun4All framework (this work has been included in a LOI document which was submitted to LRD from the sPHENIX Collaboration).
3) We started on assembling three more mRICH modules (the optical components only) at GSU in anticipation of more mRICH performance tests. A near future possibility is in Hall D at JLab using secondary electron beams.

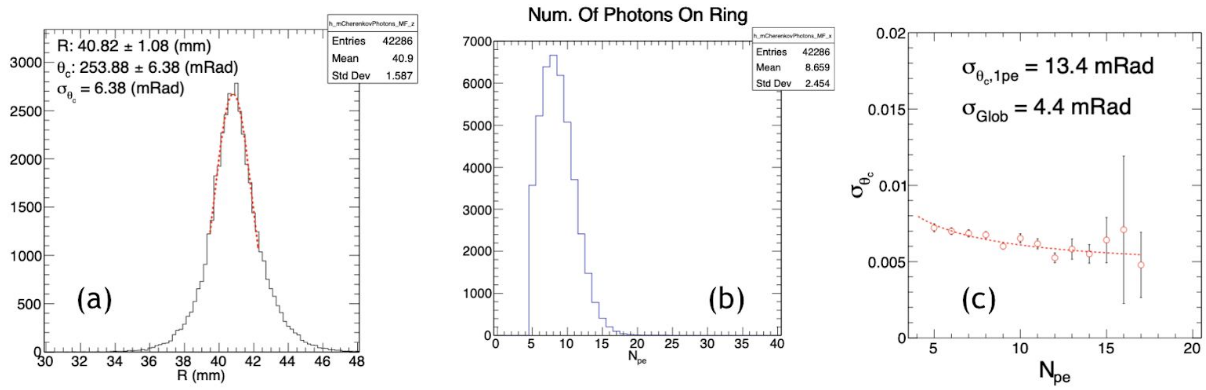


Figure 2.3.1: Preliminary results of the mRICH performance study obtained from an analysis of the second mRICH beam test data taken with a 120 GeV/*c* proton beam incident perpendicularly at the center of the mRICH: (a) extracted ring radius; (b) number of photons on the ring; and (c) single-photon Cherenkov angle resolution.

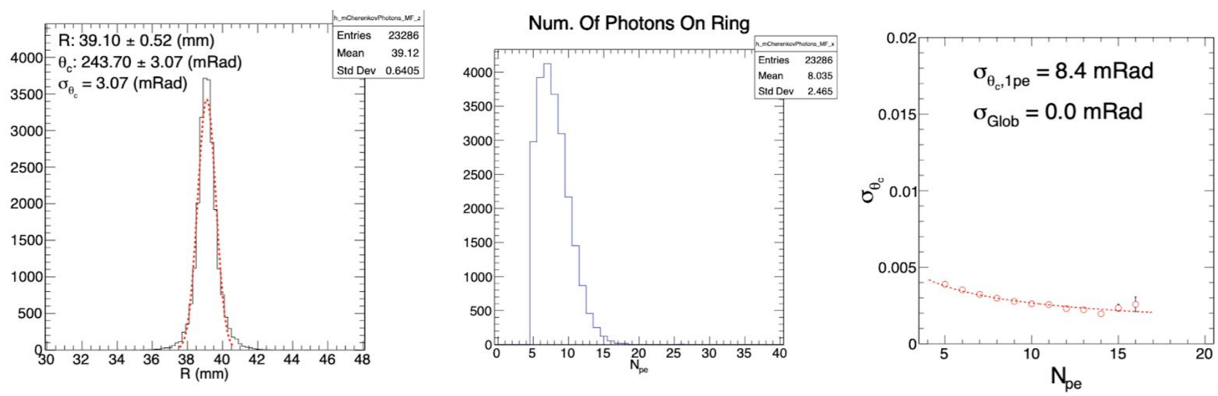


Figure 2.3.2: Preliminary results of the mRICH performance study with a GEANT4-based simulation: (a) extracted ring radius; (b) number of photons on ring; and (c) single photon Cherenkov angle resolution.

2.3.1.3 What was not achieved, why not, and what will be done to correct?

We were not able to take mRICH data with beam hodoscopes during the second beam test because of a readout issue. We are currently assessing the impact of the lack of hodoscope signals on the meson beam data set. The main concern is whether we are able to determine the incident-beam direction.

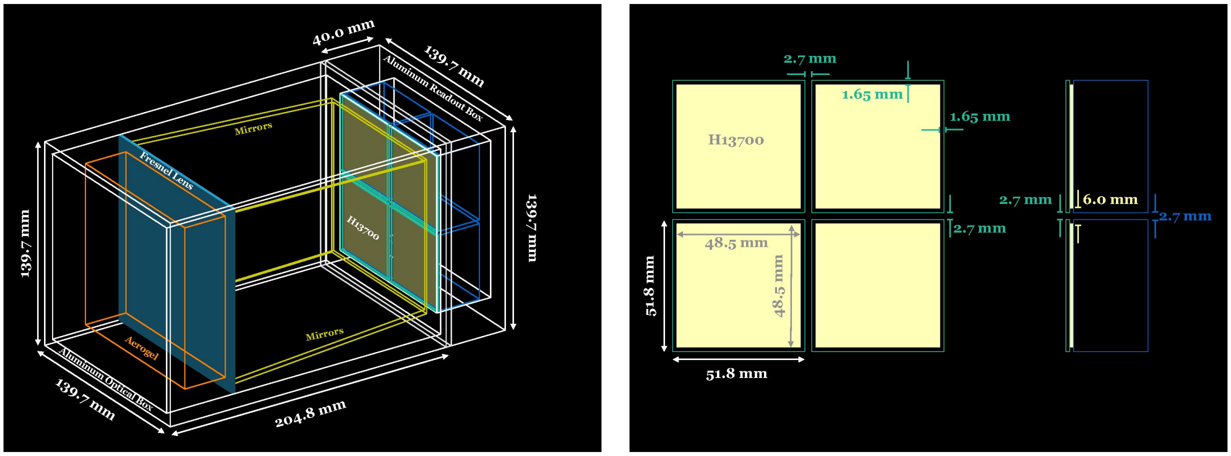


Figure 2.3.3: The most-up-to-date mRICH display in the GEANT4 simulation that matches with the detector configuration during the second beam test at Fermilab in 2018. The left display shows the whole detector setup annotated with proper dimensions. The detailed sensor plane implementation is shown on the right.

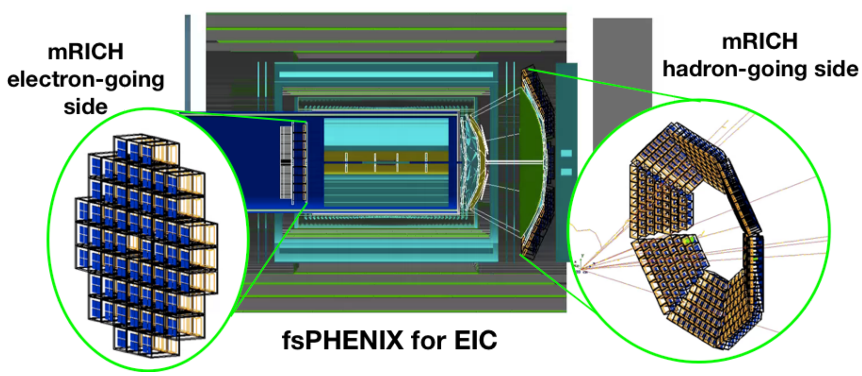


Figure 2.3.4: The mRICH subsystem implemented in the EIC Day-One-Detector based on sPHENIX. The individual mRICH modules can be mounted projectively toward the interaction point.

2.3.2 Future

2.3.2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The major activity in the next funding cycle is to continue the mRICH data analysis and to fine tune the simulation configuration to match with the beam-test data. Specifically, we plan to quantitatively assess the effects of the optical alignment on the mRICH performance. These include the focal plane location, the sensor-plane orientation, *etc*. We also want to quantify the temperature-dependent noise levels in the data sample that was taken with three SiPM matrices.

For the first time, we used SiPM matrices (from Hamamatsu, 16 x 16 matrix, 3 mm x 3 mm pixel size) to read out signals from the mRICH prototype. The successful implementation and operation of the SiPMs was indeed a significant achievement in this R&D activity. SiPMs were used due to the requirement for photosensors functioning in a high magnetic field in the EIC experiments. Figure 2.3.5 shows the assembly of the SiPM matrices mounted on cooling blocks (left) and the cooling system used for the test (right). The test data were taken with the 120-GeV primary proton beam at cooling temperature of -30^0 C, -20^0 C, -10^0 C, 0^0 C and room temperature. Figure 2.3.6 shows three examples of cumulative ring images from this test.

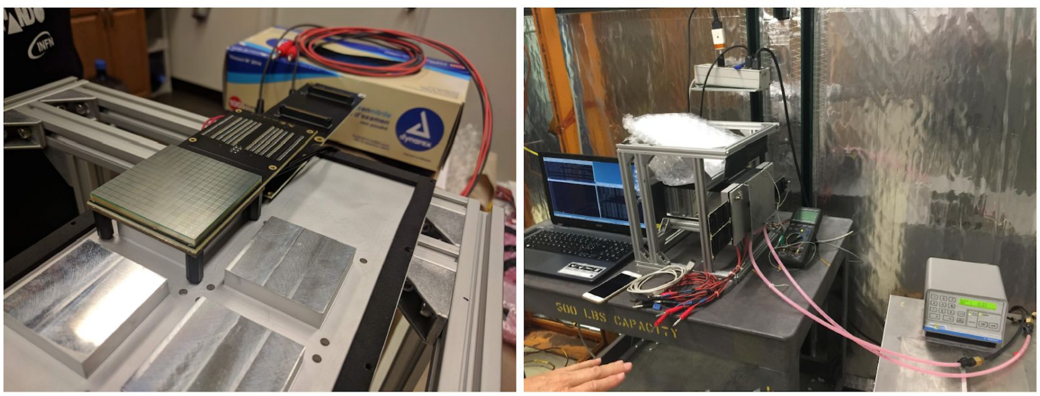


Figure 2.3.5: SiPM matrices setup (left picture) and the cooling system, liquid cooling (right picture). Only three matrices were available for the test.

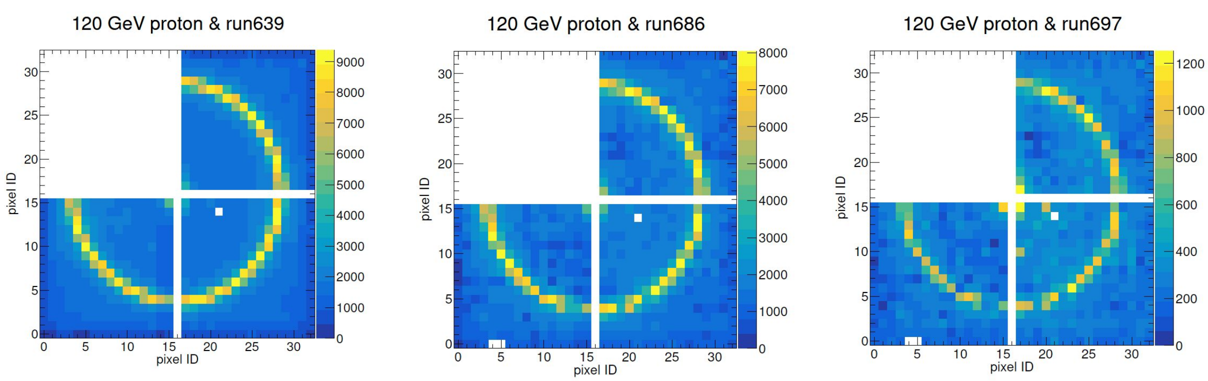


Figure 2.3.6: Examples of cumulative ring images from the second mRICH-prototype beam test using three SiPM matrices. **Left:** at a cooling temperature of -20^0 C. **Middle:** at a cooling temperature of 0^0 C. **Right:** at room temperature.

The third mRICH beam test is under preparation. This will likely take place in Hall D at JLab. GSU group is constructing three more identical mRICH modules at the time of writing of this report.

2.3.2.2 What are the critical issues?

There are two critical issues which will affect the success of the third mRICH test: (1) a working tracking system which will be read out together with photosensors of mRICH; (2) the acquisition of aerogel blocks for this test.

References

[1] C.P. Wong, et. al., *Modular focusing ring imaging Cherenkov detector for electron-ion collider experiment,* NIM A 871, 13 (2017).

2.4 High-Performance DIRC

A radially-compact detector based on the DIRC (Detection of Internally Reflected Cherenkov light) principle is a very attractive solution for the EIC, providing particle identification (e/π, π/K, K/p) over a wide range of angles and momenta. The DIRC is a type of RICH detector using rectangularly-shaped radiators made of synthetic fused silica that also function as light guides, transporting the Cherenkov photons to an expansion volume, where they are recorded by an array of photon sensors. During the photon transport the emission angle of Cherenkov photons with respect to the particle track is maintained and can be reconstructed from measured parameters. DIRC detectors are inherently 3D devices, measuring the image location on the detector surface (*x, y*) and the time of arrival of each photon (*t*).

The High-Performance DIRC design developed for the EIC detector is inspired by the original DIRC detector used by BaBar and by the PANDA Barrel DIRC detector currently in development. The baseline design, implemented in a Geant4 simulation, is shown in Fig. 2.4.1b. The radiators are 4.2-m long each, with a cross-section of 17 mm x 32 mm. Eleven such bars are placed side-by-side, separated by a small air gap, into a light-tight bar box. The 16 bar boxes are arranged in a barrel with a radius of 1 m around the beam line. Mirrors are attached to one end of each bar. On the opposite end, where photons exit the bar, a special 3-layer spherical lens is coupled to a large prism-shaped expansion volume, made of synthetic fused silica. A closeup view of this region is shown in Fig. 2.4.1c. The prism has a 38° opening angle, and dimensions 285 mm x 390 mm x 300 mm. The detector plane of each prism is covered by 3 mm x 3 mm pixels for a total of about 208k channels to record the location and arrival time of the Cherenkov photons.

A key component to reach the required performance is a special 3-layer spherical compound lens. This lens contains a layer of the high-refractive index material, sandwiched between two layers of synthetic fused silica. The two radii of the 3-layer lens were optimized to remove aberrations present in standard lenses by first defocusing and then focusing the photons to create a flat focal plane, matching the geometry of the prism expansion volume.

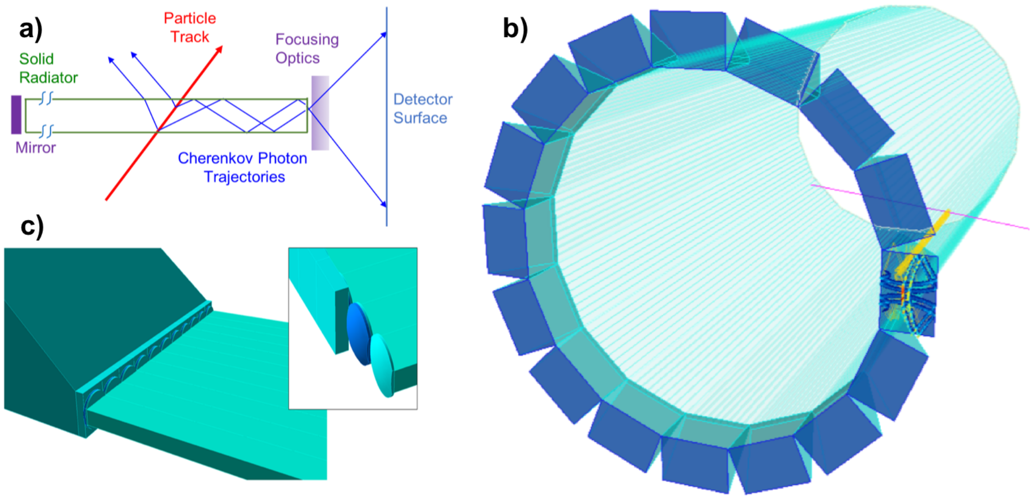


Figure 2.4.1: a) Schematic diagram visualizing the DIRC principle. b) Geant4 geometry for the simulation of the High-Performance DIRC where one can see the accumulated Cherenkov-photon hit pattern for charged kaons. c) The fused silica prism expansion volume, a row of spherical three-layer lenses with high index of refraction (no air gaps) and the radiator bars. The insert shows the individual lenses and layers of the spherical lens system.

2.4.1 Past

2.4.1.1 What was planned?

A key hardware-related activity planned for the second half of FY19 and the beginning of FY20 was to prepare the prototype transfer from GSI, Germany to the U.S. We also planned to continue the radiation-hardness study of the various optical DIRC materials by irradiating samples with a ^{60}Co source at BNL. Two prototype lenses, made with alternative high refractive index materials, were expected to be produced. The laser setup to evaluate the lenses performance was supposed to be upgraded. The hiring of a new postdoc was planned.

2.4.1.2 What was achieved?

The administrative part of the prototype transfer between GSI, CUA, and University of Stony Brook is in progress.

A successful radiation-hardness study was performed at BNL, and three materials were tested up to 2 Mrad. We also performed initial photo-annealing and luminescence tests.

Two custom-made 3-layer spherical lenses, using sapphire or PbF_2 as the middle layer, were ordered in FY19. The first one was fabricated and received in September 2019, the second is being manufactured, on track for delivery in the spring of 2020.

The upgrade of the laser setup to evaluate the focusing properties of lenses was started and is in an advanced state.

Transfer of the PANDA Barrel DIRC Prototype

After completion of the PANDA Barrel DIRC beam-test campaigns, several of the key components of the prototype have become available for use by the EIC DIRC effort on the basis of a long-term loan or an in-kind contribution. The mechanical prototype structure, as well as at least one narrow bar, one wide plate, one prism expansion volume, several PHOTONIS XP85012 MCP-PMTs (6.5mm x 6.5 mm pixel pitch), and PADIWA/TRB readout electronics for initial tests will be transported to the U.S. for future prototype beam tests at Fermilab or BNL. This will significantly reduce the financial investment required to set up the first prototype for the test of lenses, sensors, and readout electronics with particle beams.

Negotiations with three potential shipping companies are ongoing. Currently, we are working on the administrative process required for a loan agreement between GSI and CUA (the U.S. receiving institution). The prototype itself will be set up in a lab at Stony Brook University. The large lab space has controlled access and all needed supplies and facilities to work on the prototype prior to test-beam measurements.

Mapping the focal plane of lens prototypes

A special laser setup was built at the Old Dominion University lab to map the shape of the focal plane of prototype lenses by rotating the lens through two parallel laser beams. The intersection point of the two laser beams determines the focal length. The lens is placed inside a glass container filled with mineral oil (with a refractive index very close to fused silica) to simulate the focusing behavior of the lens in the DIRC, where it will be placed between the bar and the prism. Each lens is supported in a custom-made 3D-printed holder that makes it possible to map out the focal plane in all three dimensions. As previously reported, the measurements performed for three of the older prototype lenses showed the desired flat shape of the focal plane for beams close to the center of the lens, in good agreement with Geant simulations. This setup was successful in determining the shape of the focal plane, but required several modifications to increase the range of incident angles, improve the precision of the measurement, and limit the systematic uncertainties, in order to have publishable results. The planned modified setup is shown in Fig. 2.4.2 as a CAD drawing (left). The photo on the right of Fig. 2.4.2 shows the advanced state of the construction of the setup. The longer oil tank is made of plexiglass and placed on a scissor lift table that will lower the tank to gain access to the optical elements, suspended above the tank, and then lift it up again. This will simplify the calibration of the setup and the change of the lenses. The rotation stage for the lens and the screen will be redesigned and will be fixed to the stable support structure above the tank. A camera with a special filter will be placed behind the tank to allow for a more precise determination of the focal length and will speed up the measurement significantly.

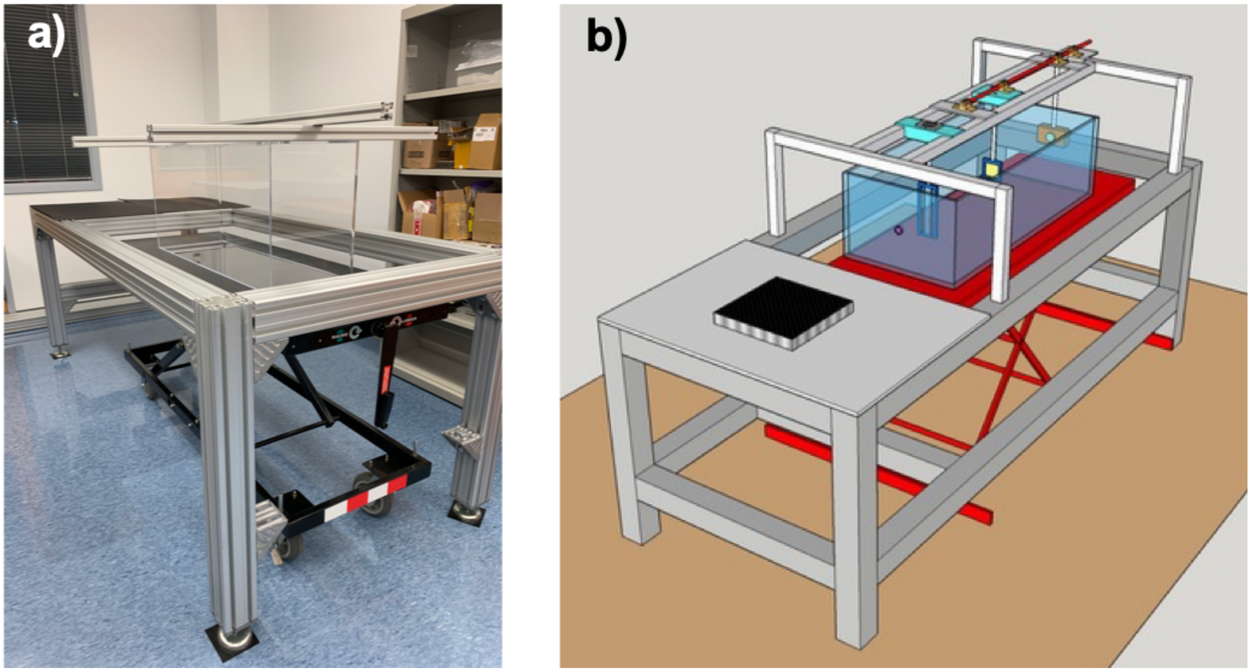


Figure 2.4.2: The improved redesigned laser setup to map the lens focal plane: (a) photo of current state, (b) CAD drawing of final design of the setup.

Radiation Hardness Measurement

The determination of the radiation hardness of materials is an important aspect of the EIC DIRC R&D. Synthetic fused silica, which is used for most of the optical components in all DIRC systems, was already extensively tested for the BaBar and PANDA DIRC counters and proved to be radiation hard. However, the middle layer of the 3-layer lens was made, in all prototypes up to now, of a high-refractive-index material lanthanum crown glass (NLaK33, S-LAH97, and S-YGH51) and our previous radiation tests strongly suggested that this material may not be suitable for the final EIC design. Several materials were studied as potential alternatives to NLaK33 and, so far, sapphire and PbF_2 are the leading candidates. All potential candidates have to be tested for radiation hardness.

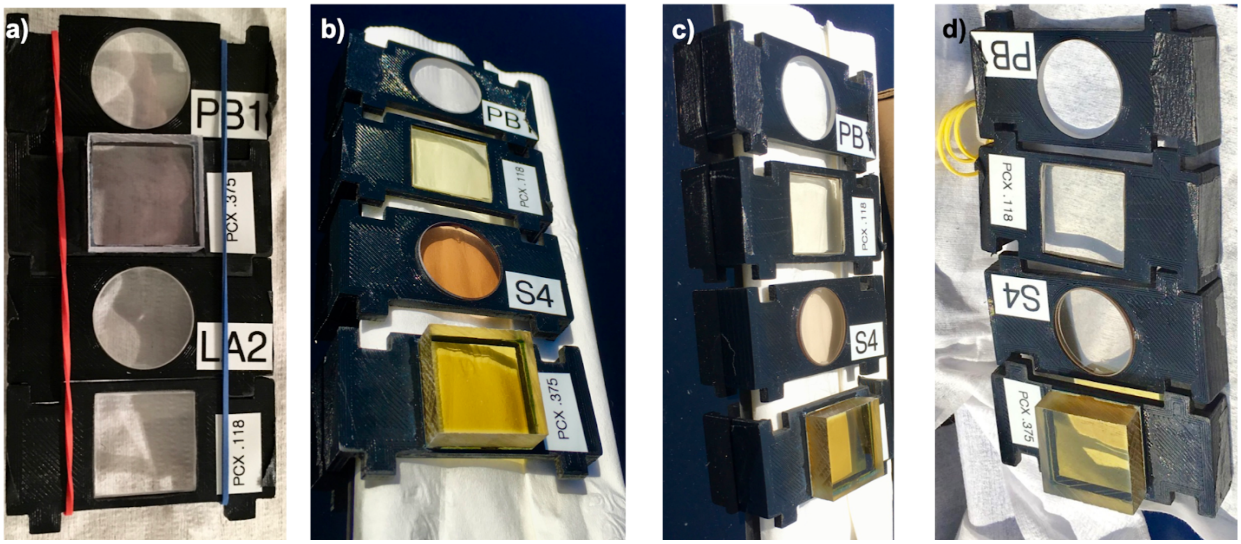


Figure 2.4.3: Samples of materials tested with a ^{60}Co source: (a) before irradiation, (b) after 2Mrad deposited dose, (c) after 2-hour-long exposure to the sun, (d) after another 2 hours of bleaching. Materials from top to bottom are: 5 mm-thick PbF_2, 3 mm-thick polycarbonate, 2 mm-thick S-YGH51, and 10 mm-thick polycarbonate.

A commonly used source for studies of radiation hardness of optical materials is ^{60}Co. Following the recommendations of the R&D review committee, we prepared a dedicated setup for radiation hardness measurements with the ^{60}Co source at the BNL radiation facility. Samples of PbF_2, sapphire, S-YGH51 (Lanthanum crown glass)), as well as polycarbonate, were exposed to accumulated doses of up to 2 Mrad. Figure 2.4.3 shows photos of selected samples tested at BNL during the second 2019 run, before (Fig 2.4.3a), and after the completion of the 2Mrad irradiation program (Fig 2.4.3b). A Fused Silica sample was never irradiated and was used as a reference in the transmission measurements. During 2019 we performed first measurements of polycarbonate with two different thickness samples. A visible colour change was observed for the S-YGH51 glass and polycarbonate samples. The color of PbF_2 sample did not change but we observed a slight drop of transmission in the 250–400nm range. The transmission of the sapphire sample was immune to the 2Mrad irradiation.

Previously, we reported the observation of a partial recovery of the transmission loss for the Lanthanum crown glass sample in the weeks after the irradiation. This time, following the irradiation and initial transmission measurement, we exposed the PbF_2, polycarbonate, and S-YGH51 samples to several hours of direct sunlight to look for effects of photo-annealing. Figure 2.4.3 shows that the Lanthanum crown glass and the thinner polycarbonate sample showed significant color bleaching after 2 hours of sunlight and additional, though weaker, bleaching after two more hours with partial recovery of the transmission loss. The PbF_2 showed a similar transmission recovery. It is interesting to note that the thicker polycarbonate sample shows very little bleaching and almost no transmission recovery, suggesting that the annealing effect of the sunlight is limited to 1–2 mm sample depth.

During the summer-2019 run we performed first luminescence tests of the materials. The samples were pressed against a single photomultiplier tube, wrapped in a light tight cover, and placed at the ^{60}Co chamber. The tube was operated at 1600 V and read out with an oscilloscope. The setup was calibrated with a fluoride sample for two tests: (a) luminescence during irradiation with a low dose rate of 2.2 rad/h and (b) luminescence a few minutes after irradiation with a high dose rate (17 krad/h). None of the materials showed proof of luminescence after irradiation, as we observed no significant signal in the PMT. We did observe a signal during the irradiation for both sapphire and S-YGH51 glass. However, improved tests have to be performed to quantify this effect. No signal was observed for lead fluoride.

Simulation framework

Detailed simulation studies of the hpDIRC design and prototypes are expected to be one of the main hpDIRC activities in FY20. Although this work will be carried out by the future DIRC PostDoc, an effort was made to set up the simulation environment. A new geometry option, based on the SLAC "ultimate DIRC" design, was implemented in the Geant4 hpDIRC simulation package to validate the framework. Figure 2.4.4 shows the Geant visualization of a single hpDIRC sector in this design, comprising 11 narrow bars with dimensions 17 mm x 32.7 mm x 3150 mm, placed side-by-side, separated by air gaps, coupled via 3-layer cylindrical lenses to a wide plate (17 mm x 360 mm x 1050 mm), which is coupled to the prism. Photons are detected by an array of MCP-PMTs, placed on the back side of the prism. The new hpDIRC design option is available for performance studies, once the new PostDoc arrives.

This "ultimate DIRC" design has the potential to further improve the Cherenkov-angle resolution and the PID performance of the hpDIRC by combining the advantages of plate and bar geometries. The finer granularity of the bars provides robustness by limiting the number of tracks entering a single radiator, while the wide plate increases the effective size of the expansion volume in one dimension (the dimension of the plate width), which starts at the location of the lenses. The design also simplifies the requirements for the cylindrical 3-layer lenses since the focal distance is significantly larger and the focal plane, therefore, less curved, and reduces optical aberrations. Possible variations of this design include focusing with spherical 3-layer lenses or eliminating the lenses by using an fDIRC-like focusing block instead of the prism.

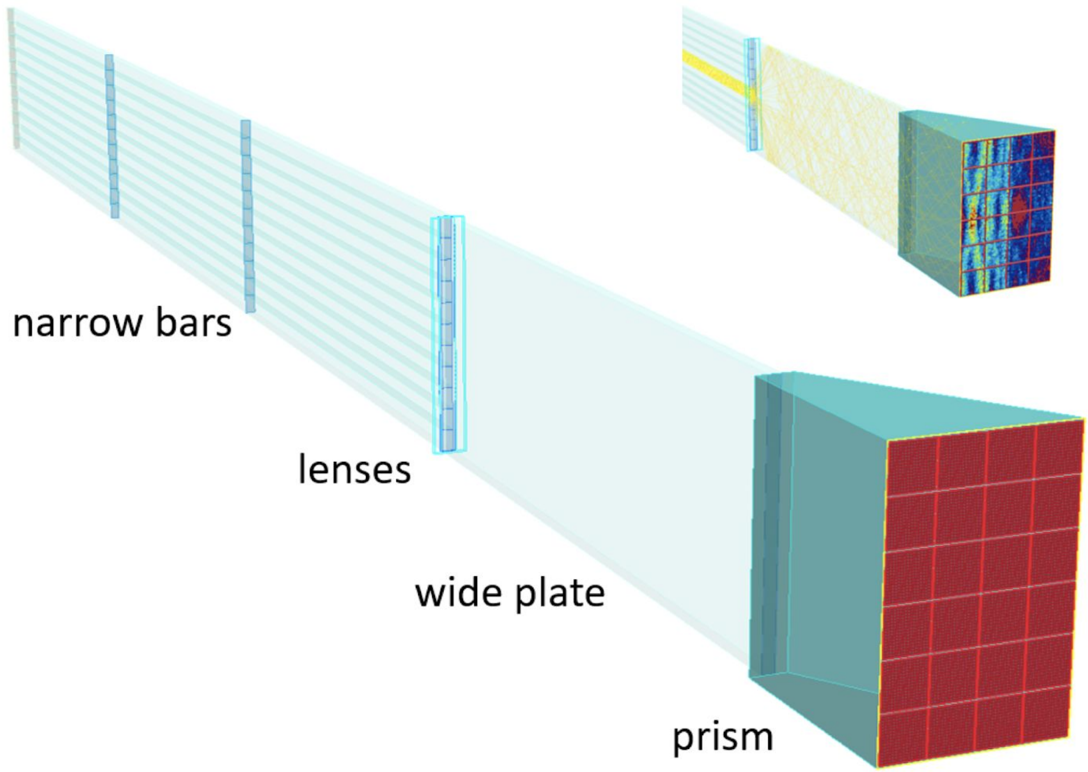


Figure 2.4.4: Geant4 geometry of an hpDIRC option based on the SLAC "ultimate DIRC" concept. The insert shows examples of photon tracks and the accumulated hit pattern for 6 GeV/*c* pions.

2.4.1.3 What was not achieved?

The process of purchasing the second prototype lens is in progress and is expected to be finalized in spring 2020.

The implementation of the High-Performance DIRC baseline design into JLab-EIC, EIC-sPHENIX, and the BeAST detector simulation frameworks is being prepared to be performed in the most FTE-efficient manner, by making use of synergies with other EIC R&D detector and software groups. Although the planned effort on the time-based imaging for the EIC DIRC had to be scaled down due to FTE limitations, some progress was made due to synergies with the PANDA Barrel DIRC group.

2.4.2 Future

2.4.2.1 What is planned for the rest of FY20? How, if at all, is this planning different from the original plan?

We expect that the transfer of the PANDA Barrel DIRC prototype to the U.S. will be completed by the summer of 2020. The components will be transported to the lab at Stony Brook University, where they will be assembled, validated, and prepared for future prototype beam tests at Fermilab or BNL.

The upgrade of the laser setup for the 3D mapping of the focal plane is expected to be completed during the spring of 2020. We plan to perform a detailed study of the focusing properties of all lenses, including the new prototypes with sapphire or PbF_2 layers, in the summer of 2020.

The activities on the detailed GEANT simulation will accelerate as soon as the new PostDoc is hired. This PostDoc will support not only the simulation design studies but also the part of prototype activities in terms of both software and hardware.

The analysis of the 2019 radiation hardness tests will be finalized and the candidate materials for the High-Performance DIRC will be studied further in terms of radio-luminescence, with the goal of publishing all radiation hardness results before the end of 2020.

We plan to prioritize the prototype and beamline simulation, as well as the validation of the prototype after shipment to the U.S., over the design optimization effort to account for the time required to hire the new PostDoc and for the new DIRC team member to become familiar with the DIRC software environment. This may shift some of the planned FY20 simulation activities and deliverables to early FY21.

2.4.2.2 What are the critical issues?

The process of hiring the PostDoc will have a major impact on the schedule for the design and prototype simulation studies and the activities on the prototype setup and preparation. Every effort is made to hire a suitable candidate as soon as possible.

The radiation-hard 3-layer lens is a core element of the High-Performance DIRC design. Validating the optical properties of the two new prototypes, made with sapphire and PbF_2, is important to confirm that these materials are indeed practical solutions for the hpDIRC lens.

The validation of the PID performance of the hpDIRC with particle beams is the key goal for FY21/22. Completing the transfer of the PANDA Barrel DIRC prototype from Germany to the U.S., in spite of administrative challenges, and testing it at Stony Brook, are critical milestones for FY20 in order to remain on track for a first beam test in FY21.

2.5 High Resolution Time-of-Flight

There were no funded activities during this period.

3. Photosensors and Electronics

3.1 Summary

The main objective of this R&D effort during the period July – December 2019 was to continue to identify and assess suitable photosensor solutions for the EIC Cherenkov Detectors and to develop electronics solutions for the readout of the Cherenkov detectors prototypes for beam tests. Ultimately, in the long term, this R&D work will allow us to make a recommendation about the best photosensors and electronics solutions for the PID detectors in EIC implementation.

3.2 Sensors in High-B Fields

3.2.1 Past

3.2.1.1 What was planned for this period?

In this reporting period we planned to study the timing resolution of a 10-μm Planacon for various B-fields and sensor orientations.

3.2.1.2 What was achieved?

In order to provide for fast timing, a different read-out scheme of the sensor was designed and manufactured by the JLab Detector Group.

For the gain characterization of the same 10-μm Planacon in the previous years, we used an internal preamplifier (x20, 250 MHz band width) mounted on the readout board that was connected directly to the backplane of the sensor. The signals were then led out of the dark box and the magnet to the fADC via a 7.62-m long micro-coax ribbon cable. Tests with a PS 417 pocket pulser showed that the micro-coax ribbon cable changed the pulse shape that made this readout unusable for timing measurements: the amplitude of the signal was decreased by 40%, the rise time was increased by 70% and the fall time increased by 25%. The micro-coax ribbon cable did not affect the pulse-integrated area, which justified it use for gain measurements, however the effect on the timing properties of the signal required a new solution. For the timing measurements, a new readout boards without preamplifiers were equipped with 5-m-long RG-188 coax cables.

Since the FY2019 R&D funds were transferred to USC very late in Spring 2019 and given the lead time of the manufacturer, the fast CAEN TDC (V1290) we purchased for the timing characterization was received only late in August 2019, well past the summer High-B test. It will be installed and implemented in the DAQ in Sumer 2020. Instead, in Summer 2019, timing measurements were attempted with a CAEN TDC V775 unit that we loaned temporarily from Hall A (JLab). Unfortunately, this TDC unit had readout issues. With no alternative TDC units that could be loaned from other JLab experiments, no timing spectra could be collected.

We used the Summer-2019 test time to evaluate the effect of the new versus old MCP-PMT readout on the gain characterization. The overall amplification of the new readout was about x20 smaller than in the old setup, however the loss of amplitude in the new readout was much smaller than in the old readout. In both readouts, external amplifications of x20 and x200 were applied by means of ORTEC VT120 Fast Timing Preamplifiers.

The gain performance of the MCP-PMT was assessed by means of the relative average-signal area, $A_{av}(B)/A_{av}(B=0\ T)$, for several rotation angles between the PMT and the B-field axes. Figure 3.2.1 shows our results. The PMT was operated in both cases at -2.65 kV.

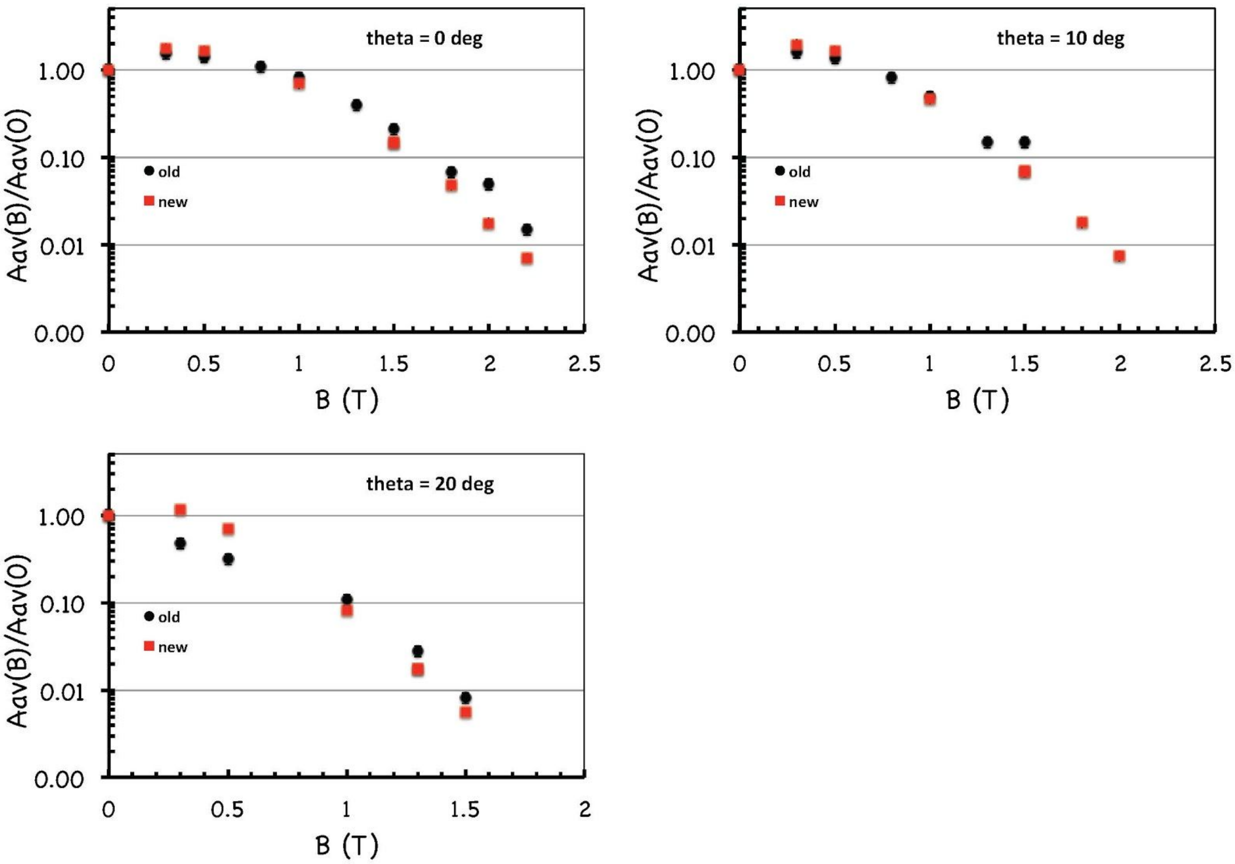


Figure 3.2.1: Comparison of extracted relative average-signal area of a 10-μm Planacon MCP-PMT with the old and the new readouts (as described in the text). Overall, both readouts yield consistent results, except at B = 0.3 T and 0.5 T at 20 deg. These discrepancies needs to be studied further in Summer 2020. The small differences observed at other fields and angles are most likely due to a too small bandwidth of the internal preamplifier that does not capture accurately the PMT fast signals. The effect of the internal preamplifier will be studied in more detail on a test bench in Summer 2020.

Overall, both readouts yield consistent results, except at B = 0.3 T and 0.5 T at 20 deg. These discrepancies needs to be studied further in Summer 2020. The small differences observed at other fields and angles are most likely due to a too small bandwidth of the internal preamplifier that does not capture accurately the PMT fast signals. The effect of the internal preamplifier will be studied in more detail on a test bench in Summer 2020.

3.2.2 Future

3.2.2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The main focus of our work in for FY20 will be on the detailed characterization of a new-generation 10-μm multi-anode Planacon in magnetic fields from 0 T up to the maximum field where the gain measurements show that the PMT performance breaks down. To that extent, we will purchase one sample of the latest-generation Planacon, XP85122-S. This unit has several improved characteristics that are relevant for the EIC-PID program, compared to the unit we tested in 2017 – 2019. The PMT has a smaller pixel size, which is critical for the validation of the hpDIRC prototype performance, and is lifetime-enhanced due to the application of the atomic-layer-deposition (ALD) technique. Tests performed by the PANDA DIRC group and the ANL group, however, suggest that MCP-PMTs with ALD treatment have worse High-B immunity than its non-ALD counterpart. Given that XP85122-S is currently the only commercially-available MCP-PMT with a pixel size that satisfies the requirements for the Cherenkov detectors, it is critical that its performance is mapped for a wide range of (B, θ, φ, HV). This new Planacon MCP-PMT will not only be used for evaluation in the High-B tests, but also, as part of the readout of the hpDIRC prototype and for the validation of the SiREAD readout of this type of PMT. In FY20, we will begin a full scan of the gain, efficiency, timing, and ion feedback as a function of (B, θ, φ , HV).

The purchase of Planacon XP85122-S was recommended in the 2019 Committee's report and $6.5 k from the DIRC budget were allocated to USC for this purpose. The rest of the PMT's cost, approximately $10k, will be covered by USC carryover R&D funds.

If we are successful to obtain a 10-μm multi-anode Photek MCP-PMT, we will perform gain and timing characterization as a function of (B, θ).

3.2.2.2 What are the critical issues?

The availability of R&D funding at the beginning of the calendar year is critical in order to keep this program within the planned timelines.

3.3 MCP-PMT/LAPPD

An important challenge for the EIC particle identification is to provide a reliable low-cost highly pixelated photosensors working in a high radiation and high magnetic-field environment. The recently commercialized Large Area Picosecond Photo-Detector (LAPPD) provides a promising low-cost photosensor solution for the EIC imaging Cherenkov sub-systems. Optimization of the sensor design for high magnetic-field tolerance, fast time resolution, and pixelated readout were performed at Argonne National Laboratory with 6 × 6 cm^2 MCP-PMTs. The effort aims to adapt the LAPPDs to the EIC requirements with optimized design parameters integrated in low-cost

LAPPD production.

3.3.1 Past

3.3.1.1 What was planned for this period?

For the period 7/1/19 – 12/31/19, we planned to: (1) Design and fabricate multi-pixel PCB board for ceramic Gen II LAPPD validation; (2) integrate the R&D results into Incom production line; (3) order components, design, and prepare to fabricate 6 cm MCP-PMT with integrated magnetic-field tolerance, RMS fast-timing design, and glass pixelated readout; (4) enhance synergetic work with electronics and Cherenkov sub-groups.

3.3.1.2 What was achieved?

In this period, our first priority was to establish effective communication with Incom to be on top of their plans for LAPPD testing and fabrication for EIC PID. Multiple communication were conducted between Argonne and Incom, as well as between eRD14 and Incom. The latter included a visit by Y. Ilieva to Incom – resulting in, among other things, letters of support for their SBIR proposal. All communications expressed the importance of providing workable LAPPDs for the coming sub-system beamline experiments within 2~3 years, as well as the critical requirement of 3x3 mm^2 pixel size. Argonne also shared its technique for achieving 1.5-T magnetic-field tolerance and 100-ps RMS timing resolution. Incom proposed Gen-III LAPPD (HRPPD) to address these issues. Figure 3.3.1 shows details of the proposed HRPPD device to address EIC-PID photosensor requirement.

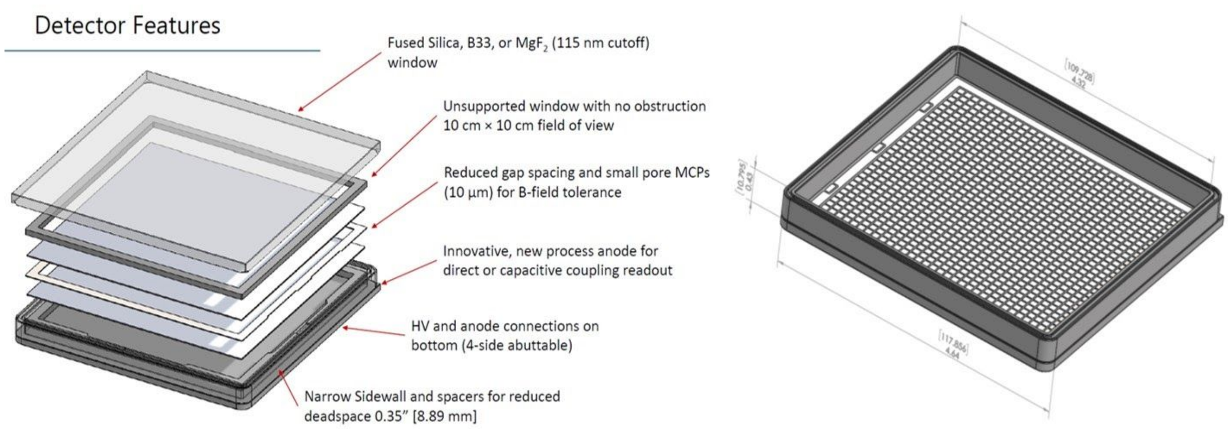


Figure 3.3.1: The proposed high-rate picosecond photodetector (HRPPD) for EIC-PID Cherenkov imaging systems. 10-μm pore size MCPs and reduced spacings design was integrated with pixelated high temperature co-fired ceramic (HTCC) anode (right) to achieve the EIC-PID photosensor requirement.

Agreement was made between Argonne and Incom on a ceramic Gen-II LAPPD loan for EIC-PID pixel-size validation. Argonne and Incom engineers together designed a multi-pixel size

PCB board specifically to be used for EIC-PIDs fine pixel validation. The board is under production, expected to be populated in January 2020 and attached to Incom Gen-II LAPPD for fine pixel validation in February 2020.

Argonne has demonstrated 1.5-T magnetic-field immunity, 100-ps RMS timing resolution on all-glass 6x6 cm MCP-PMT device and 3x3 mm^2 pixel size with capacitive coupling through glass test. Integration of the capacitive coupling through glass into the all-glass device design would provide a cheaper solution for the EIC-PID MCP-PMT photosensor. Meanwhile, replacing the glass window with fused silica will provide the Argonne MCP-PMT with UV detection capability. Argonne ordered anode materials and fused silica top windows, and prepared to start the integrated MCP-PMT fabrication in January 2020. The fabricated device will be bench tested at Argonne, and then send to BNL to attach to a GEM based board, which is prepared for a Spring-2020 Fermilab beamline test. The device will eventually be put into Fermilab test beam for pixel readout validation.

ASoC v2 evaluation board from Nalu Scientific, LLC was on loan at Argonne to obtain hands-on experience with their fast electronics with MCP-PMT/LAPPD. The ASoC v2 evaluation board was attached previously to Argonne MCP PMT and Incom LAPPDs for initial testing by a Nalu engineer. After becoming familiar with the onloan ASoC v2 evaluation board at Argonne, we plan to place this board in JLab Hall C high-background environment for high-rate performance test.

Two papers, on the 1.5-T magnetic field immunity, 100-ps RMS timing resolution of an all-glass 6x6 cm MCP-PMT device and on the 3x3 mm^2 pixel size with capacitive coupling through glass test were completed and are now going through internal review before submission.

3.3.2 Future

3.3.2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

In the rest of FY20, we plan to continue MCP-PMT/LAPPD fabrication and characterization work as scheduled:

- Complete ceramic Gen-II LAPPD fine pixel-size evaluation.
- Fabricate two integrated 6 cm MCP-PMTs.
- Bench test the fabricated 6 cm MCP-PMTs.
- Evaluate the pixelated electronics readout and Zigzag readout at Fermilab test beam.

3.3.2.2 What are the critical issues?

Given the accelerated timeline for EIC-PID to demonstrate sub-system readiness in 4 years, the emergent for Incom to provide workable HRPPDs and to be characterized in all aspects becomes the most critical issue.

3.4 Readout Sensors and Electronics for Detector Prototypes

3.4.1 Past

The data acquisition system for the mRICH beam test was provided by the INFN group led by Marco Contalbrigo. There were four Hamamatsu H13700 modules mounted at the sensor plane. The H13700 readout consisted of three circuit boards [Tur15]. The adapter board is a passive board with mounting connectors to couple the MA-PMTs socket to the electronics. The ASIC board is based on the MAROC3 chip by OMEGA [Ome18], served by voltage regulators (Analog Devices AD5620). The FPGA board is based on the Xilinx Artix7 and uses the Finisar FTE8510N1LCN optical transceiver to connect to the SSP/VSX DAQ system developed at JLab [Ray14].

The electronics for DIRC beam tests at CERN were mostly provided by the PANDA DIRC group as part of the GSI infrastructure that was made available to the EIC R&D program (although some compatible items were also procured as part of eRD4 prior to formation of the eRD14 consortium).

3.4.1.1 What was planned for this period?

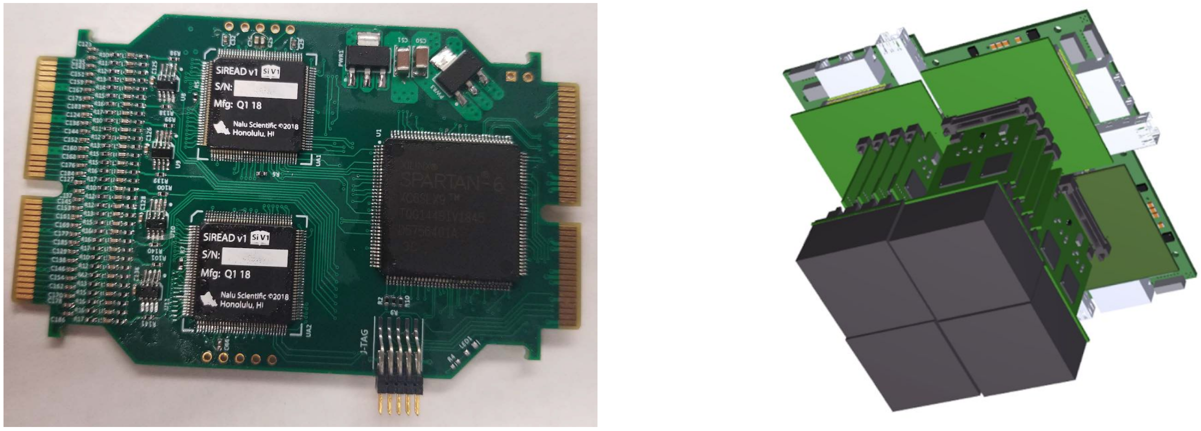
The development of the readout electronics follows a multi-stage strategy. The goal is to provide a solution for all PID detector R&D needs, and a template for a final system to be used in the full EIC detector. The detailed schedule is adapted to the planned R&D schedule of each system. To experimentally demonstrate the PID performance, the DIRC prototype will eventually have to be instrumented with small-pixel sensors with good timing (<100 ps rms), for which the next-generation SiREAD chip from Nalu Scientific would be ideal. An SiREAD prototype has already been developed through SBIR funding. The new DIRC readout needs to be ready when the prototype is moved to the U.S. (The previous tests at CERN used sensors and electronics available at GSI.) The initial priority is, thus, to develop a readout for the RICH detectors, and in particular the mRICH, which carried out its second beam test in the first half of 2018. The similarity between the sensors considered for the dRICH and mRICH also allows the latter to serve as a (sensor and readout) prototype for the former. It is our hope that even if the detailed requirements of the two systems would eventually diverge somewhat, a high degree of commonality can be retained. We also plan to use SiREAD for the next iteration of the readout for the RICH detectors – allowing for further synergies.

The primary goal for this reporting period was the development of a readout firmware for upcoming beam tests, which will follow the very successful mRICH beam tests at Fermilab in April 2016 and June 2018. A goal of this next beam test is to fully verify the PID capability by using the same photosensors, which utilize finer pixel size (3 mm x 3 mm) from Hamamatsu: H13700A multi-anode PMTs and cooled MPPC (SiPM) arrays. For this test, there is no requirement for <100 ps timing (which the CLAS12 electronics cannot fulfill). The availability of the two readout prototypes allow for a direct comparison of the performance. One prototype will again use a readout based on an evolution of the tested CLAS12 electronics provided by the INFN group (M. Contalbrigo) and one based on the sampling electronics from the U. Hawaii group (G. Varner) and Nalu Scientific, LLC (I. Mostafanezhad). The latter was initially based on the TARGETX chip, used in the electronics provided by that group for the Belle II upgrade at KEK. However the longer-term goal has been to switch over to the new SiREAD chip, the experience gained with an intermediate version based on TARGETX, as well as the cross reference with the CLAS12 electronics, will be an important part of the R&D process. The 64-channel SiREAD chip (32ch prototype) is currently being developed by Nalu Scientific, a small business specializing in System-on-Chip data acquisition systems, which has recently been awarded multiple DOE Phase I and Phase II SBIRs to develop the next generation readout electronics for HEP/NP applications. Crucial to demonstrating readiness of the SiREAD solution is the development of configuration and acquisition firmware compatible with the CLAS12 readout, and so that development was a major focus of this period.

3.4.1.2 What was achieved?

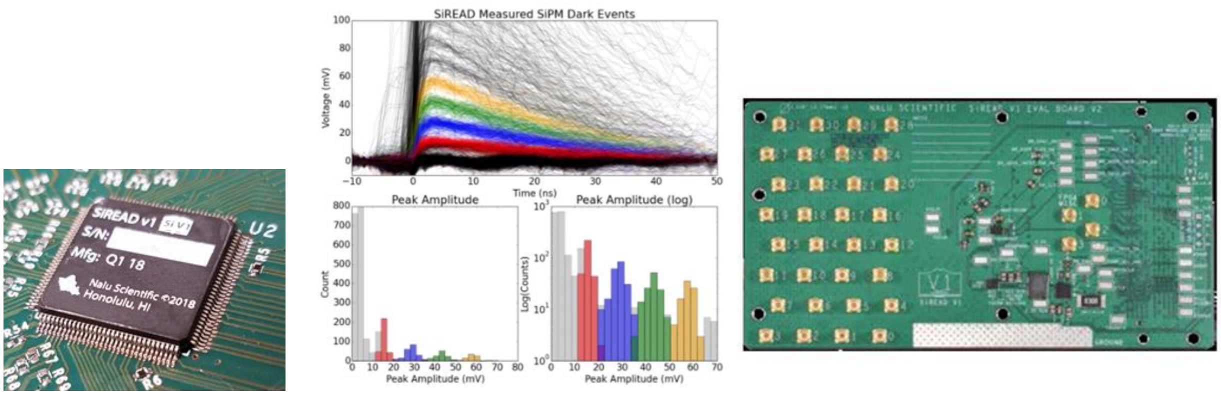
U. Hawaii (G. Varner) is working with Nalu Scientific (I. Mostafanezhad) to develop a readout solution for mRICH using new readout ASICs. The SiREAD chip was fabricated and tested at Nalu Scientific through funding from the DOE SBIR program. A rev 1.0 PCB was designed and fabricated to support this SiREAD chips, as seen in Fig. 3.4.1. Such a design allows to rapidly test the electronic performance of the readout scheme when coupled with the MCP PMT or SiPM array. A single PMT readout consists of 4 of these 64-channel daughtercards coupled to a H13700 PMT. A rendering of the expanded version, to read out 1024 channels for a future beam test can also be seen in Fig. 3.4.1. If there is a decision to move to a SiPM array, the design is inherently flexible enough to allow such migration with minimal amount of redesign. Figure 3.4.2 shows the fabricated 32-channel prototype SiREAD chip with 1 GSa/s digitization and System-on-Chip digital processing capabilities. The SiREAD was connected to a SiPM element and dark counts were recorded on a testbench. In order to perform additional testing on SiREAD, a 32 channel evaluation board was designed and developed with each channel connected to a dedicated MMCX connector as shown in Figure 3.4.2c. This board is currently under testing and evaluation at several labs and facilities.

In parallel, the INFN group worked on upgrading the readout electronics (based on the JLab CLAS12 RICH electronics) for reading out the high-channel density H13700 modules and explored the option for using SiPM array with cooling. An effort is being made to secure a complete back-end chain for the EIC R&D. Such a chain is instrumental to serve during the development and at beam tests. It will be particularly effective at the new facility in Hall D now in preparation, to allow long-term tests complemented with a tracking system. Using INFN funds, a VSX crate was already acquired and a SSP module is being processed in conjunction with a common JLab procurement to limit the cost. The progress is on track. This may allow us to test both photosensors during the next mRICH beam test.



(a) **(b)**

Figure 3.4.1: Images of the readout electronics developed for the H13700 PMT. (a) fabricated 64 channel readout for 64 channels, and (b) rendering of four modules, each containing four 64 channel daughtercards, abutted to read out 1024 channels.



(a) **(b)** **(c)**

Figure 3.4.2: (a) Fabricated prototype 32-channel SiREAD chip. (b) Dark count measurements on a SiPM using the SiREAD chip showing 1pe, 2pe,... waveforms and histograms. (c) 32 channel MMCX connector breakout board for SiREAD evaluation.

3.4.2 Future

3.4.2.1 What is planned for the next funding cycle and beyond? How, if at all, is this planning different from the original plan?

The consortium is developing readout electronics for future R&D needs. The plan is on track and will result in a system that can satisfy the needs of all the Cherenkov detectors (DIRC, dRICH, mRICH). The first SiREAD-based MA-PMT readout version will be supplied for the next mRICH beam test at Fermilab. Given the capabilities of the 2nd generation SiREAD, we will develop and adapt readout boards to connect the SiREAD to the data collection FPGA, for a more compact and performant readout scheme.

References:

[Tur15]
http://infn.fe.infn.it/~mcontalb/JLAB12/RICH_midterm_review/RICH_Electronics_Turisini.pdf

[Ome18]
http://omega.in2p3.fr/index.php/download-center/doc_details/393-proceedingsieeenss2010maroc3.html

[Ray14]
https://coda.jlab.org/drupal/system/files/pdfs/HardwareManual/SSP/SSP_Module_HallD_v1.2.pdf

4. Manpower

Abilene Christian University

Rusty Towell, Faculty

Argonne National Laboratory

Junqi Xie, Staff Scientist, 25% of time spent on project

Lei Xia, Staff Scientist, 10% of time spent on project

Edward May, Argonne Associate, 20% of time spent on project

Tim Cundiff, Electronics Engineer, 5% of time spent on project

Brookhaven National Laboratory

Mickey Chiu, Staff Scientist

Andrey Sukhanov, Electronics Engineer

Rob Pisani, Scientific Associate

Catholic University of America

Grzegorz Kalicy, Faculty, 50% of research time on project

Duke University

Zhiwen Zhao, Research Professor

Georgia State University

Xiaochun He, Faculty, 20% of time spent on the project

Murad Sarsour, Faculty, 5% of time spent on the project

Xu Sun, postdoc, 50% of time on the project

Sawaiz Syed, temp staff, 10% of time on this project

GSI Helmholtzzentrum für Schwerionenforschung

Roman Dzhygadlo, Staff Scientist, 25% of time spent on project

Carsten Schwarz, Staff Scientist, 15% of time spent on project

Jochen Schwiening, Senior Staff Scientist, 15% of time spent on project

Howard University

Marcus Alfred, Faculty, 25% of time spent on project

INFN

Marco Contalbrigo, researcher, 10% of time spent on project

Evaristo Cisbani, researcher, 10% of time spent on project

Vincenzo Lucherini, researcher, 10% of time spent on project

Marco Mirazita, researcher, 10% of time spent on project

Aram Movsisyan, post-doc, 10 % of time spent on project

Luca Barion, post-doc, 40% of time spent on project supervised by M. Contalbrigo

Jefferson Lab

Carl Zorn, Staff Scientist

Los Alamos

Hubert van Hecke, Staff Scientist (ret.)

Old Dominion University

Charles Hyde, Faculty, 30% of research time on project

Stony Brook University

Pawel Nadel-Turonski, Adjunct Professor, 30% of research time spent on project

University of Hawaii

Gary Varner, Faculty, 10% of time spent on project

Tommy Lam, Undergraduate Student, 100% of time until departed for Virginia Tech to attend graduate school, supervised by G. Varner

Emily Lum, Undergraduate Student, 50% time, supervised by G. Varner

Nathan Park, Undergraduate Student, 50% time, supervised by G. Varner

University of Illinois at Urbana-Champaign

Matthias Grosse-Perdekamp, Faculty

University of South Carolina

Yordanka Ilieva, Faculty, 30% of time spent on project

Alan Rowland, Undergraduate Student, 17% of time spent on project (8 weeks), located at Jefferson Lab and USC, supervised by Y. Ilieva

Brandon Tumeo, Graduate Student, 5% of time spent on project (2 weeks), located at Jefferson Lab, supervised by Y. Ilieva

Colin Gleason, Postdoctoral Fellow, 5% of time spent on project (2 weeks), located at Jefferson Lab, supervised by Y. Ilieva

Include a list of the existing manpower and what approximate fraction each has spent on the project. If students and/or postdocs were funded through the R&D, please state where they were located and who supervised their work.

5. External Funding

ANL

- ANL-LDRD project: Tomography at an Electron-Ion Collider: Unraveling the Origin of Mass and Spin, Oct 1, 2019 – Sep 30, 2020: $150k

ODU

- FY16-FY19: 50/50 form DOE Grant funding and University funds for ODU Technician time: $6k per year.
- FY20: 50/50 form DOE Grant funding and University funds for ODU Technician time: $10k.

GSU

- University funds provided the major portion of the support for a graduate student and for the research staff. We also used the university funds for purchasing building materials for construction of the mRICH prototypes and the supporting frames.

GSI

- Replacement for rotating stage and DAQ computer in preparation for PANDA DIRC prototype transfer to the U.S. in FY20: $8k.
- Spherical lens prototype (non-radiation hard) test production: $42k.
- GSI travel funds for annual DIRC@EIC meeting at JLab and R&D committee meetings at BNL: $12k.

UHawaii

- DOE Detector R&D (Hawaii Grant Task F) support for new detector development and ASIC training stewardship, roughly $100k annually, 25% spent this reporting period.

INFN

- dRICH: prototype mechanics, procurement of gas and aerogel for tests; mRICH+dRICH: SiPM and cooling system; electronics; travel expenses: €21k.

BNL

- Infrastructure and staff salary for the radiation hardness tests of DIRC and mRICH optical materials.

Jefferson Lab

- Salary of staff (detector experts, DAQ, electronics, technicians), facilities, equipment, and infrastructure for the High-B MCP-PMT evaluations.
- Conference space for the annual DIRC collaboration meeting, phone conferencing for the bi-weekly consortium meetings and any other consortium-related remote meetings.

Nalu Scientific

- SBIR grant for developing the SiREAD chip for digitizing SiPM waveforms with applications in EIC PID.

See also the respective sections for more details on TOF, photosensors, etc.

6. Publications

6.1 In Preparation

A. Del Dotto et al., *Event based inverse ray-tracing reconstruction for RICH detector*, to be published in NIM (likely first half of 2019).

Junqi Xie et al., *MCP-PMT development at Argonne for particle identification*, proceeding of DIRC2019, to be submitted to JINST. (Jan 2020).

Junqi Xie et al., *ALD-coated microchannel plate photomultiplier with fast timing and magnetic field immunity*, to be submitted to NIM A. (early 2020).

6.2 Recently Published or Submitted

Junqi Xie, Marcel Demarteau, Edward May, Robert Wagner, and Lei Xia, *Fast-timing microchannel plate photodetectors: design, fabrication and characterization*, Review of Scientific Instruments 90, 043109 (2019). https://doi.org/10.1063/1.5063825

Mohammad Hattawy, Junqi Xie, Mickey Chiu, Marcel Demarteau, Kawtar Hafidi, Edward May, Jose Repond, Robert Wagner, Lei Xia, and Carl Zorn, *Characteristics of fast timing MCP-PMTs in magnetic fields*, Nucl. Instr. and Meth. A 929, 84 (2019). https://doi.org/10.1016/j.nima.2019.03.045

E. Cisbani, A. Del Dotto, C. Fanelli, M. Williams *et al.*, *AI-optimized detector design for the future Electron-Ion Collider: the dual-radiator RICH case*, submitted to Journal of Instrumentation, Nov

2019. https://arxiv.org/abs/1911.05797

7. Presentations

J. Xie, *Application of MCP-PMT/LAPPD for EIC Particle Identification*, CPAD Instrumentation Frontier Workshop 2019, 8 – 10 December, Madison, WI, 2019.

A. Rowland (EIC PID Collaboration), *Studies of the Gain of Small-Pore Size Microchannel Plate Photomultipliers in High Magnetic Fields*, poster presentation at Discover USC, April 26th, Columbia, SC, 2019.

A. Rowland (EIC PID Collaboration), *Studies of the Gain of a Small-Pore Size Microchannel Plate Photomultiplier in High Magnetic Fields*, poster presentation at the Conference Experience for Undergraduates at the Fall 2019 Meeting of the APS Division of Nuclear Physics, 14 – 17 October, Crystal City, VA, 2019.

X. He (EIC PID Consortium), *mRICH*, invited talk, Streaming Readout V, RIKEN BNL Research Center Workshop, November 13 – 15, 2019.

E. Cisbani (mRICH and dRICH Groups), *RICH detectors development for hadron identification at EIC: design, prototyping and reconstruction algorithm*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.

C. Fanelli, *Machine learning for RICH counters*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.

G. Kalicy (EIC PID Consortium), *High-Performance DIRC Detector for future EIC DetectOR*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.

J. Xie, *MCP-PMT development at Argonne for particle identification*, invited talk, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.

G. Varner, *Performance of the imaging Time Of Propagation detector during the first Belle II Physics run,* invited talk, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.

G. Varner, *Recent developments in paradise: fast waveform sampling readout electronics for finely pixelated photosensors in Hawaii,* presentation, DIRC2019: Workshop on fast Cherenkov detectors, 11 – 13 September, Castle Rauischholzhausen, Germany, 2019.